Distinguishing new physics via multi-messenger tests of the Distance Duality Relation

Matteo Martinelli
25/08/2026

Based on:
C. De Leo, MM, R. D'Agostino, G. Gianfagna, C. Martins (2025)
MM, D. Sapone (2026)

What is the DDR?

In a cosmological model based on a metric theory of gravity, with massless particles travelling on null geodesics, and with the number of such particles conserved, cosmological distances satisfy the Etherington relation or DDR.

Etherington, Philos. Mag. (1933)

$$\boxed{d_L(z) = (1+z)^2 d_A(z)}$$

Within the current status of cosmology (tensions, dark components,...), testing for our fundamental assumptions is necessary.
If any of such assumption is violated, we expect to observe deviations from such a relation.

Parameterized deviations from the DDR

What we want to constrain is the deviation from the DDR, encoded in the function

$$\eta(z) = \frac{d_L(z)}{(1+z)^2 d_A(z)} \qquad\qquad \eta(z) = (1+z)^{\epsilon(z)}$$

Avgoustidis, Verde, Jimenez 2009

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The exponent is usually parameterized in order to obtain constraints

$$d_{\mathrm{L}}(z) = (1+z)^{2+\epsilon_0} d_{\mathrm{A}}(z) \qquad \epsilon(z) = \begin{cases} \epsilon_0 & \text{if } z < z_* \\ \epsilon_1 & \text{if } z \geq z_* \end{cases}$$

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Other possible parameterizations, more interesting for H_0 tensions, but less for theoretical modelling

Teixeira et al. 2025

How do we constrain DDR?

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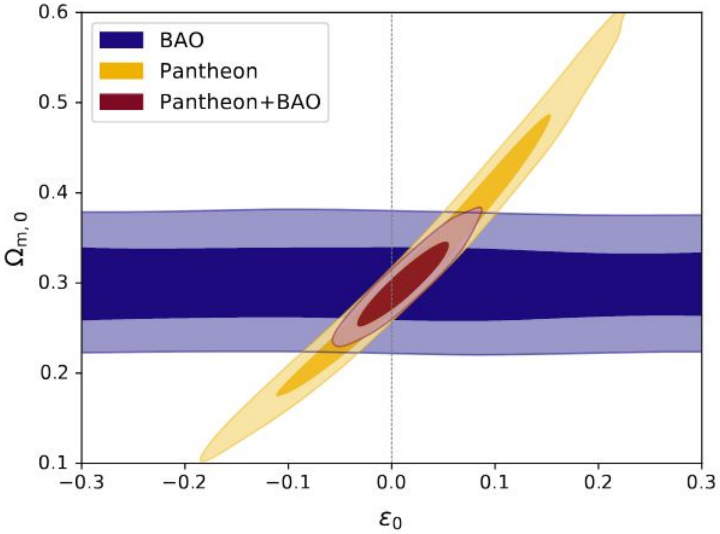

[Martinelli et al. 2020]

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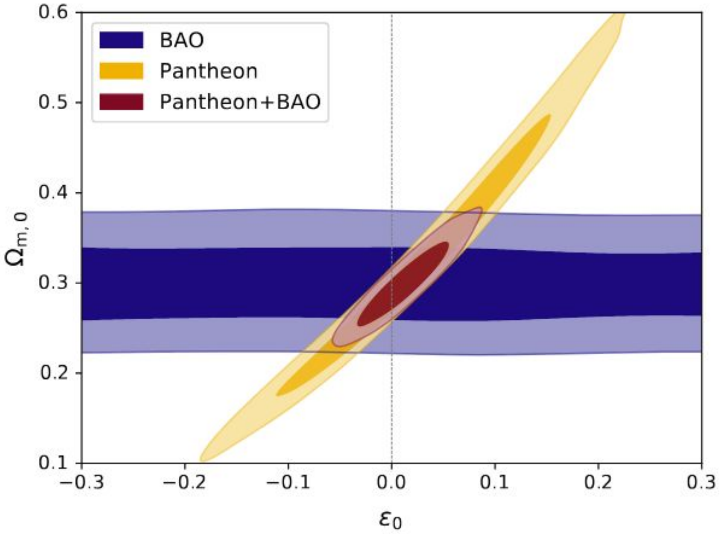
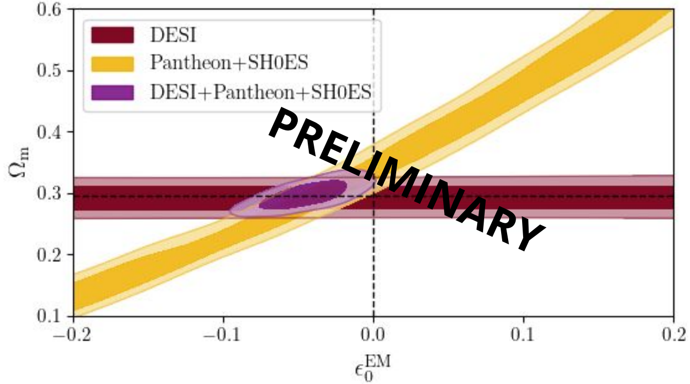


Martinelli et al. 2020



How can we distinguish DDR breaking mechanisms?

Several mechanisms can lead to a violation of DDR.

- photons-axions coupling
- modified gravity
- dust
- ...?

Looking at SNIa+BAO it is difficult to distinguish between mechanisms.

N. Hogg, MM, S. Nesseris (2020)

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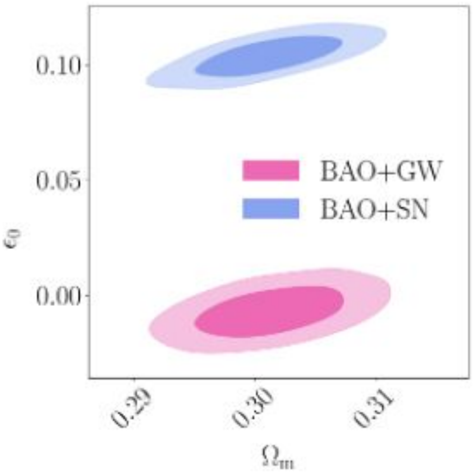
GW observations can test if gravitons and photons behave in the same way (MG) or if DDR is violated differently in the two sectors

Distinguishing classes of models

We find that the combination of BAO (SKAO), SN (LSST) and GW (ET) allows to distinguish between models affecting photons (particle physics) and those changing also gravitons propagation (gravity modifications?)



Assuming that the same parameters rules GW and EM violations, one find tensions if DDR violations are related only to photons

De Leo, Martinelli, D'Agostino, Gianfagna, Martins 2025

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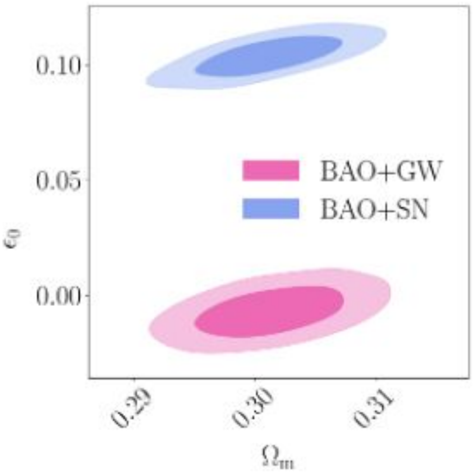

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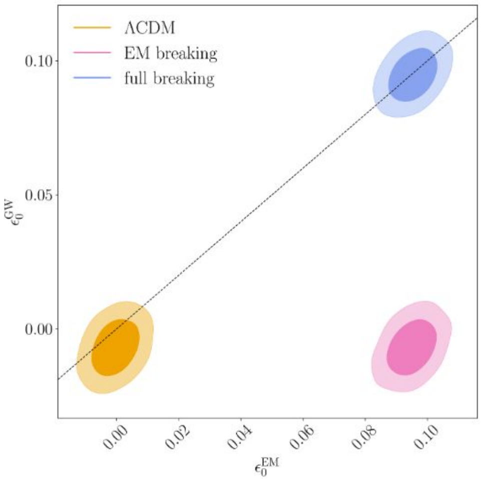
Assuming independent DDR braking, we can safely combine all data and measure the violation separately for EM and GW



De Leo, Martinelli, D'Agostino, Gianfagna, Martins 2025

Avoiding parametrizations: the Cosmic Tetrarchy

Previous results assume a functional form and a fiducial cosmology, but we can avoid this

Looking at BAO observables, we can define 2 ways to estimate the sound horizon

$$R_\perp(z) = \frac{r_d}{r_d^{fid}} = \frac{D_M(z)}{D_M^{fid}(z)\,\alpha_\perp(z)}$$

$$R_\parallel(z) = \frac{r_d}{r_d^{fid}} = \frac{D_H(z)}{D_H^{fid}(z)\,\alpha_\parallel(z)}$$

Depending on which observable we use to estimate D_M and D_H, we can probe different assumptions

Avoiding parametrizations: the Cosmic Tetrarchy

- Combining BAO and SNIa

$$R_{\perp}^{\mathrm{SN}}(z) = \frac{1}{1+z}\frac{d_{\mathrm{L}}(z)}{D_{\mathrm{M}}^{\mathrm{fid}}(z)\,\alpha_{\perp}(z)}$$

assumes DDR

$$R_{\parallel}^{\mathrm{SN}}(z) = \frac{d_{\mathrm{L}}(z)}{(1+z)D_{\mathrm{H}}^{\mathrm{fid}}(z)\,\alpha_{\parallel}(z)}\left[\frac{d'_{\mathrm{L}}(z)}{d_{\mathrm{L}}(z)} - \frac{1}{1+z}\right]$$

assumes DDR + flatness

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assumes DDR + flatness

- Combining BAO and CC

$$R_{\perp}^{\rm CC}(z) = \frac{c}{D_{\rm M}^{\rm fid}(z)\,\alpha_{\perp}(z)}\int_0^z \frac{{\rm d}z'}{H(z')}$$

assumes flatness

$$R_{\parallel}^{\rm CC}(z) = \frac{c}{H(z)\,D_{\rm H}^{\rm fid}(z)\,\alpha_{\parallel}(z)}$$

FLRW

Reconstruction approaches

GP approach

- RBF kernel to reconstruct all data (smooth!)

$$K(x, x') = \sigma^2 \exp\left[-\frac{(x-x')^2}{2\ell^2}\right]$$

- Bayesian propagation of hyper-parameters uncertainty

$$\Sigma_{total} = \mathbb{E}_\theta[\Sigma_{GP}(\theta)] + \mathrm{Var}_\theta[\mu_{GP}(\theta)]$$

- Simple differentiation thanks to GP properties

$$\mathbf{f}'^* = \frac{\partial K(\mathbf{X}^*, \mathbf{X})}{\partial \mathbf{X}^*}\left[K(\mathbf{X}, \mathbf{X}) + C\right]^{-1} \mathbf{y}$$

Binned approach

- Joint observations vector with associated covariance

$$\begin{aligned} \mathbf{x} \quad = \quad & \left(\mu_1, \ldots, \mu_n,\ H_1^{-1}, \ldots, H_n^{-1},\right. \\ & \left.\alpha_{\|,1}, \ldots, \alpha_{\|,n},\ \alpha_{\perp,1}, \ldots, \alpha_{\perp,n}\right) \end{aligned}$$

- Bin observations on a priori defined bins (centred on BAO observations)

- Numerical derivatives (noisy!)

$$\begin{aligned} \left.\frac{df}{dz}\right|_{z_i} \approx & -\frac{h_+}{h_-(h_- + h_+)} f_{i-1} + \frac{h_+ - h_-}{h_- h_+} f_i \\ & + \frac{h_-}{h_+(h_- + h_+)} f_{i+1}, \end{aligned}$$

Ratios reconstruction

We reconstruct the observables, their derivatives and integrals using Gaussian Processes or a binned approach on DESI DR2, Pantheon+ and CC data.

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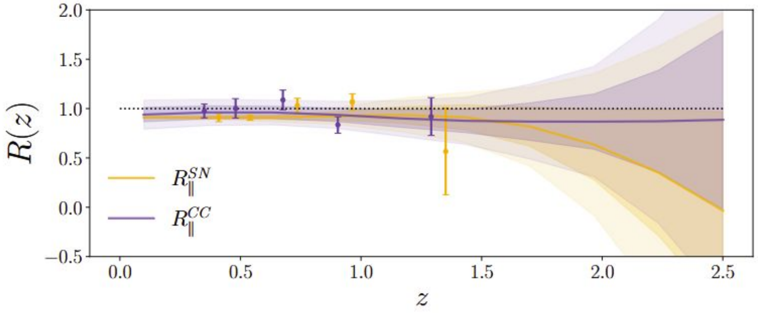

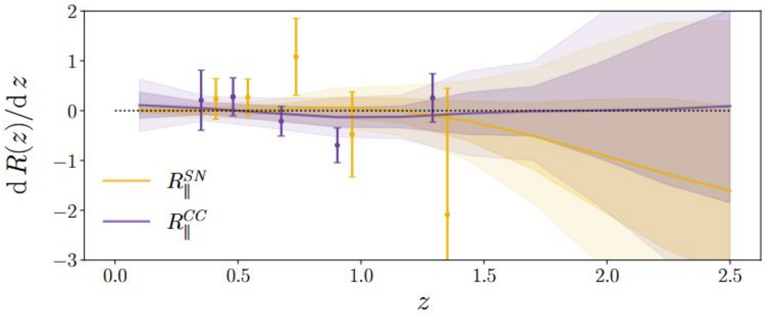

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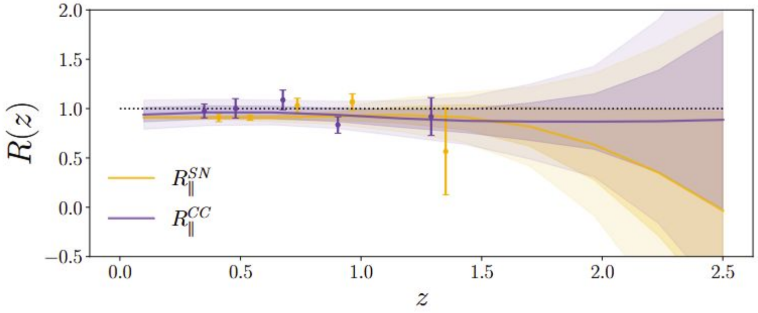
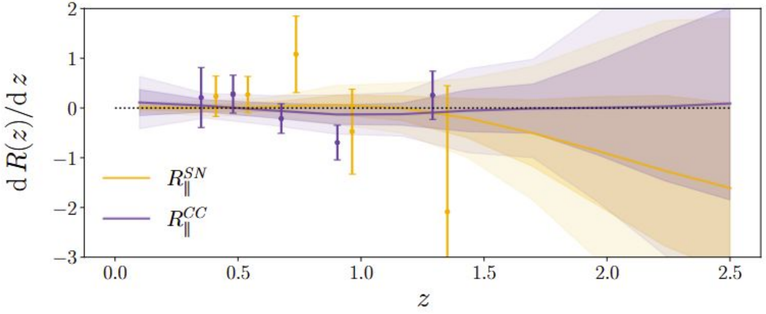




If all assumptions hold, all estimators need to be consistent and compatible with a constant.

Deviations from this behaviour would allow to identify what is breaking.

Estimators and tension quantification

With mean and covariances for the functions and derivatives, obtained with GP and binned approaches, we construct a joint mean and joint covariance

$$\mathbf{\Sigma} = \begin{bmatrix} \mathbf{C}_{d_\mathrm{L}} & 0 & 0 \\ 0 & \mathbf{C}_{1/H} & 0 \\ 0 & 0 & \mathbf{C}_{\alpha_\perp,\alpha_\parallel} \end{bmatrix}$$

We draw samples from these and combine them to obtain realizations of the estimators. We can then compare them with each other or with a constant

$$\chi^2_{ij} = [\mathbf{R}_i - \mathbf{R}_j]\ \mathbf{\Sigma}^{-1}_{\mathrm{tot}}\ [\mathbf{R}_i - \mathbf{R}_j]^\mathrm{T}$$

$$\chi^2_{\mathrm{const}} = \mathbf{R}'\,\mathbf{\Sigma}^{-1}_{R'R'}\mathbf{R}'^\mathrm{T}$$

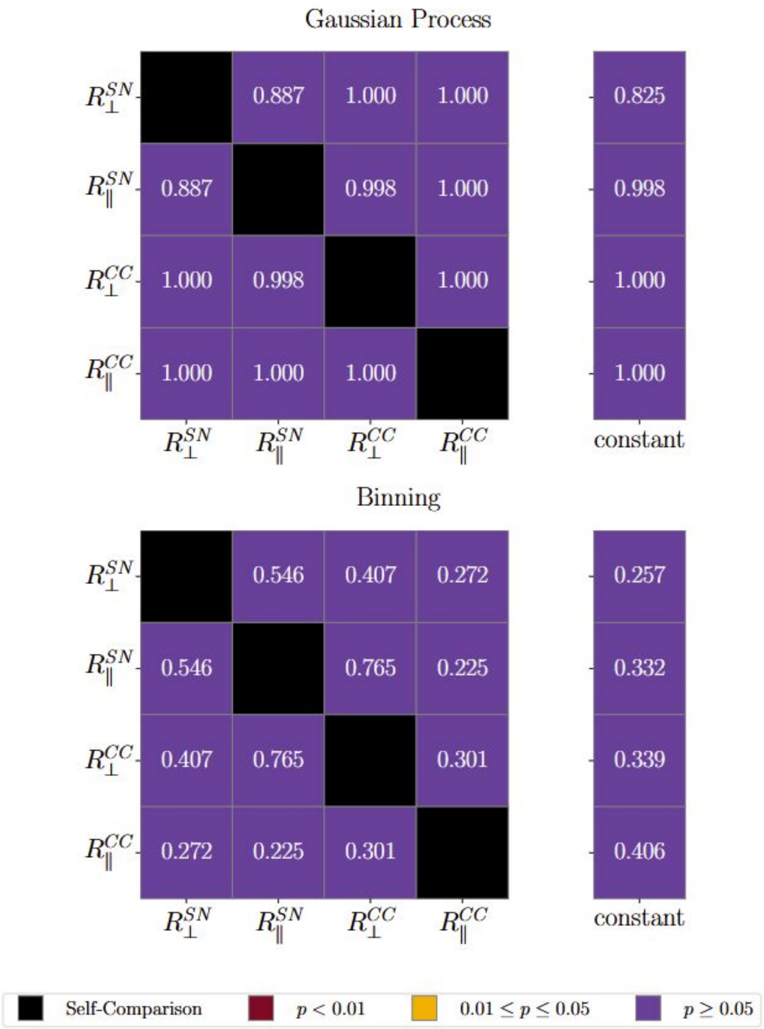
$$p_{ij} = 1 - \mathrm{CDF}(\chi^2_{ij}, N_{\mathrm{dof}})$$

No evidence of violations

Current data show no problem running this test.

SN based estimators score worse than CC based ones when testing their derivatives

Worth looking with improved data if this persist (DDR violation)



Outlook

- Current data seem to hint to a violation of DDR when analyzed in parametric form;
- this might be some other tension being moved to DDR parameters. We need other approaches to test possible mechanisms
- More agnostic consistency tests show no deviation from standard behaviour
- Including GW observations can be a game changer: measuring DDR in EM and GW sectors allows to distinguish physical mechanisms
- **Need bright sirens!**

Advertisements

If you are interested in reproducing or extending our analysis, you have all the tools available on GitHub!

chiaradeleo1/CANDI
for parametric DDR

CANDI

Code for **AN**alysis of modified **D**istance-duality with cosmological **I**nference

matmartinelli/CoRe
for Gaussian Process or binned analysis

CoRe (/ˈkoːre/) : Cosmological Regressor

A modular Python framework for performing non-parametric reconstructions of cosmological functions and propagating those results into derived cosmological quantities. This toolkit is designed for high-performance inference, with a **JAX** module for Gaussian Processes, a binning-focused class, and an interface to **CAMB** for theoretical cosmological quantities.